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Modelling and analysis of the flood risk at Cavaillon City, Haiti

Adermus JOSEPH[1], Nyankona GONOMY[2], Yves ZECH[3], Sandra SOARES-FRAZÃO[4]

[1.] *Université catholique de Louvain, Ecole Polytechnique de Louvain, e-mail : zoadermus@yahoo.fr*
[2.] *Université d'Etat d'Haïti, Faculté d'Agronomie et de Médecine Vétérinaire, e-mail : ngonomy@yahoo.fr*
[3.] *Université catholique de Louvain, Institut de Mécanique, Matériaux et Génie Civil, e-mail : yves.zech@uclouvain.be*
[4.] *Université catholique de Louvain, Institut de Mécanique, Matériaux et Génie Civil, e-mail : sandra.soares-frazao@uclouvain.be*

ABSTRACT. – In Haiti, the vulnerability of urban populations in river flood corridors has disastrous socio-economic consequences on the living conditions of these communities. Mapping of areas prone to this type of risk is not sufficiently developed in Haiti, which complicates the implementation of strategies for the effective management of flood risk. This paper presents a methodological approach allowing to draw up a risk map of the city of Cavaillon, which is confronted to periodic flooding by the Cavaillon river flowing through the city. The reconstruction of the riverbed and floodplain geometry using a differential GPS and a novel drone-based photogrammetry technique made it possible to construct a hydraulic model of the river and to calculate the flow in the river for scenarios corresponding to different periods of return. The vulnerability of the different areas in the city was established using an Analytic Hierarchy Process. Various criteria of vulnerability were identified and their respective weight progressively determined from discussions between local decision-makers. Finally, considering the extent of the inundated area following recent Hurricane Matthew that particularly affected the zone, a vulnerability mapping was drawn for the town of Cavaillon.

Key-words: Flood mapping, inundation, one-dimensional model, flood scenarios, vulnerability

Modélisation et analyse du risque d'inondation dans la ville de Cavaillon en Haïti

RÉSUMÉ. – En Haïti, la vulnérabilité des populations urbaines vivant dans les couloirs d'inondation des rivières a des conséquences socio-économiques désastreuses sur les conditions de vie de ces communautés. La cartographie des zones sujettes à ce type de risque est insuffisamment développée en Haïti, ce qui complique la mise en place de stratégies adéquates pour la maîtrise des risques d'inondation. L'article présente une approche méthodologique en vue de dresser une cartographie du risque pour la ville de Cavaillon, périodiquement confrontée à des inondations dues au débordement de la Rivière de Cavaillon qui envahit régulièrement la ville. La détermination de la géométrie du lit de la rivière et des plaines d'inondation à l'aide d'un GPS différentiel et d'une technique originale de photogrammétrie à partir d'un drone a permis la construction d'un modèle hydraulique de la rivière et le calcul de l'écoulement pour des scénarios correspondant à différents temps de récurrence. La vulnérabilité des différentes parties de la ville est identifiée à partir de de la méthode de hiérarchie multicritère (Analytic Hierarchy Process). Différents critères de vulnérabilité ont été identifiés et leurs poids respectifs progressivement déterminé à partir de discussion entre les preneurs de décision. Finalement, en considérant l'extension des zones inondées lors du récent cyclone tropical Matthew, qui a particulièrement touché cette région, une carte de vulnérabilité a pu être dressée pour la ville de Cavaillon.

Mots-clés : Zones inondables, cartographie, modèle unidimensionnel, scenarios de crue, vulnérabilité

I. INTRODUCTION

The degraded environment and the difficult socio-economic conditions in which the Haitian population lives increase its vulnerability to natural disasters such as hurricanes, earthquakes, landslides and floods, which are frequent in Haiti. The impact of these calamities on the national economy is significant because they affect lives, properties and basic infrastructure, such as roads, bridges, buildings, energy plants and sanitation equipment. Damages due to flooding in cities and towns along the watercourses and on the runoff paths are estimated at billions of US dollars each year [Gonomy 2012]. Flooding in previous years at Fonds-Verrettes, Gonaïves, and most recently Hurricane Matthew (October 2016) in the southern part of the country, illustrate the extent of the damages. This high-risk situation in the country calls for collective consciousness and must force the State to strengthen its disaster strategies and approaches through a better knowledge of the realities on the ground.

The Haiti disaster risk reduction strategy is based on the effective implementation of the National Risk and Disaster Management Plan (NRDP), which considers interventions at the local level [Constant, 2009].

Such a management plan is founded not only on study of the hazards but also on an analysis of the vulnerability of the territories, regarding as well goods as people. However, most of the criteria that can be used for estimating this vulnerability are subjective. The so-called Analytic Hierarchy Process [Saaty, 1980] is a powerful tool for giving a frame to assess this vulnerability.

Within the frame of a cooperation project funded by ARES-CCD (Académie de Recherche et d'Enseignement Supérieur – Commission de la Coopération au Développement, Belgium), the present work is part of a broader study aiming at improving the ability of Haitian institutions to better manage their rivers and prevent or at least decrease potential damages of flood events.

Part of the work is devoted to the development of a methodology aiming at constructing simple and efficient hydraulic models for Haitian rivers, based on the existing knowledge and on field surveys, and using free modelling tools, considering the limited available resources in the country. Such modelling of flood flows in rivers must allow, after a thorough analysis of the vulnerability of the territories, to carry out a flood risk analysis of the zones situated in the flood corridors of the rivers. As an example, this strategy of modelling and analysing flood risks is done for the Cavaillon River and specially the town of Cavaillon, located in the Southern department of Haiti (Fig. 1).

The paper is organized as follows. First the study site and the available data are presented. Then, the hydraulic model of the river is briefly described, including upstream and downstream boundary conditions. This model is calibrated using the available discharge and water level data, and the methodology proposed to study flood scenarios on the river is presented. Then, the vulnerability of the area according to the characteristics of all the issues in the part of the city recently flooded after the passage of Hurricane Matthew is presented. Finally, the results are discussed and perspectives are given for future work.

II. DESCRIPTION OF THE STUDY SITE

The town of Cavaillon is located on the national highway No. 2, which connects the capital Port-au-Prince to the city of Les Cayes, capital city of the Southern Department of Haiti. The municipality of Cavaillon covers an area of 214 km² and has a population of about 44 276 inhabitants. The town of Cavaillon is built at the foot of mountains on a small plateau and is divided in two parts by the Cavaillon River. The altitude of the natural terrain is relatively low especially on the right bank of the river. The city infrastructures consist of two bridges on the river, residential and public buildings, and irrigation canals in the irrigated perimeters near the city.

The Cavaillon River flows over approximately 50 km (Fig. 2) until reaching the sea. The studied reach has a length of 25 km, located between the Dory weir and Grand Place. The river reach inside the city is 4649 m long with an average width of 60 m.

Like for most of Haitian rivers, neither topographic nor bathymetric data was available for the considered reach. Regarding the minor bed, 96 cross sections (Fig. 3(a)) were surveyed manually with a differential GPS device [Joseph *et al.*, 2015]. Regarding the flood plains, the

Fig. 1 : *Localisation of the study area.*

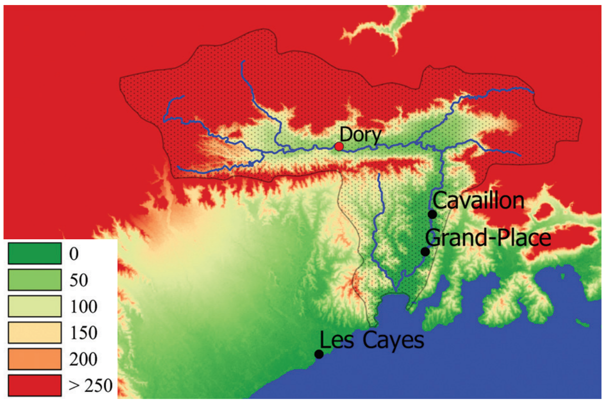
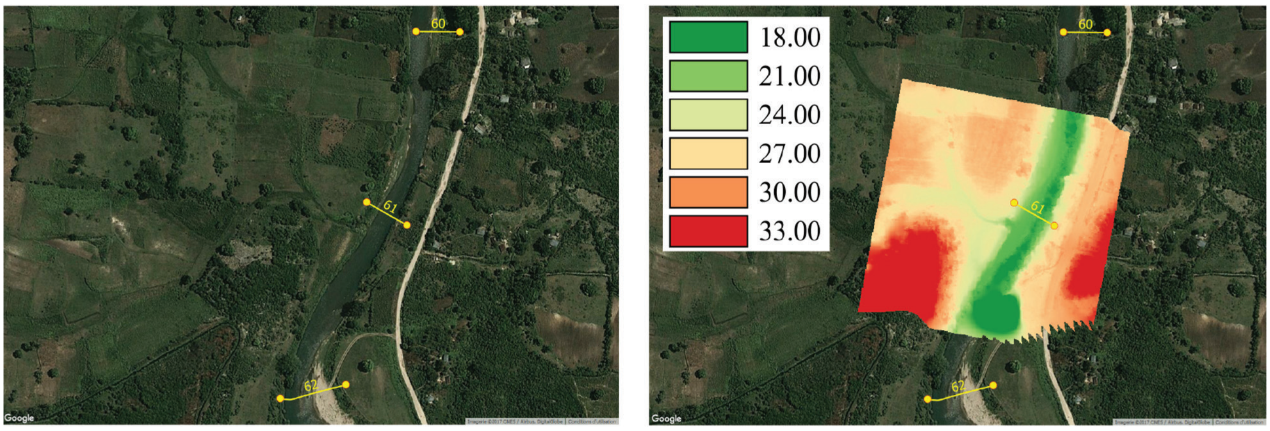


Fig. 2 : *Watershed and level contours of the Cavaillon River area (in meters).*



(a) Satellite view around section 61

(b) Dense DTM from UAV photogrammetry (levels in meters)

Fig. 3 : *Aerial view of surveyed cross-sections and of the dense DTM obtained from UAV photogrammetry.*

only available Digital Terrain Model (DTM) at this time was a coarse 30-m mesh, so it was decided to apply a novel but rather cheap photogrammetry techniques using a Unmanned Aerial Vehicle (UAV) flying over potentially flooded areas [Macq, 2016]. This latter technique, while used in unusual and difficult conditions of accessibility and energy supply, revealed to be surprisingly accurate, at least regarding relative values of ground elevation (Fig. 3(b)). A dense DTM could be defined from those measurements at least for the flood plains that are accessible during the dry season. The mesh size of this new dense DTM has a resolution of about 0.10 m. Recently, a new systematic survey of the country yielded a 1.50-m resolution DTM, better than the former 30-m one but not so accurate than the drone-driven DTM.

The challenge is to link correctly this DTM to in situ measurements of the cross-sections. An example is shown in Fig. 4, always for the same cross-section 61. The red curve (corresponding to the red line between the two yellow points in Fig. 3(b) was obtained by in situ measurements using the differential GPS, while the blue curve (corresponding to the black line in Fig. 3(b), i.e. outside the two yellow points) represents the section of the detailed drone-driven DTM. As the in situ measurements and UAV flight were carried out during the dry season, a part of the two curves may overlap, showing a good continuity between both types of measurement. Of course the bottom part of the DTM blue line is not completely aligned to the in situ measurement, as the photogrammetry fails in accurately representing the levels below the water surface, even if the water depth is limited.

Regarding discharge data on the Cavaillon River, only old data are available: daily maximum and minimum flows recorded at the Cavaillon station during the period of 1925 to 1941 and a second series from 1976 to 1980 [Joseph, 2006; Gonomy, 2012]. In these datasets, a maximum discharge higher than 600 m^3/s was observed although the annual flow modulus of the river is estimated at 8 m^3/s. According to local witnesses and flood marks after the recent Hurricane Matthew, it seems that the discharge of the Cavaillon River during this event was probably over 600 m^3/s.

In the frame of this project, before Hurricane Matthew, only discharges up to 20 m^3/s were measured in the river. Unfortunately, during the hurricane itself, many of the measurement devices were destroyed and discharge and water level could not be recorded until the peak flow.

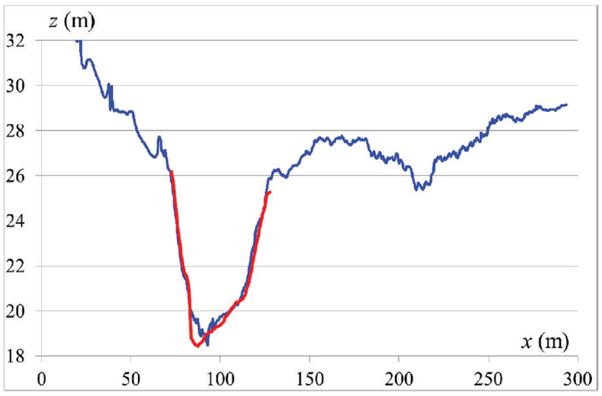


Fig. 4 : *Cross section 61. Comparison between in situ measurements (red line) and the corresponding cross-section of the dense DTM obtained from UAV photogrammetry (blue line).*

III. HYDRAULIC MODEL

III.1. Bathymetry

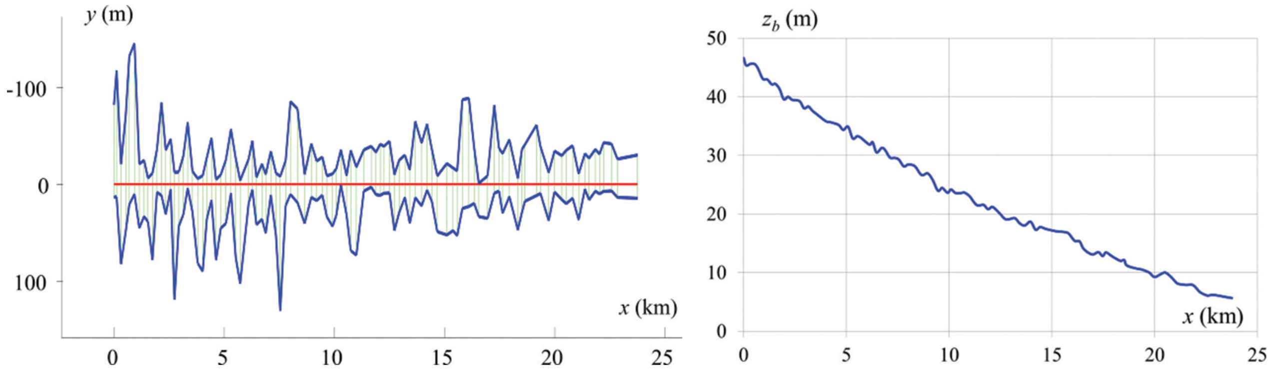
A one-dimensional model of the studied river reach was constructed based on the collected field data, as well for the minor bed as for the flood plains. As can be observed in Fig. 5, where plan view of the minor bed and bed profile of the considered part of the Cavaillon River are represented, abrupt changes in the cross-section width occur in the river, with local adverse slopes.

III.2. Boundary conditions

In the studied area the river is expected to present a subcritical flow. That means that two boundary conditions are required: the discharge at the upstream end of the reach and a water level at the downstream end.

The upstream end of the study reach is located at the Dory weir (see localisation in Fig. 2). As can be observed from Fig. 6, the weir was designed with a typical Creager profile, but it was seriously damaged during previous floods, even before Hurricane Matthew. In particular, the crest line is no more horizontal and the downstream concrete apron was lifted upwards at some places, probably due to important under pressures during flood events.

Such deviations from standard conditions require the determination of a specific stage-discharge relationship that could



(a) Schematic plan view (the red line is the thalweg) (b) Bed profile

Fig. 5 : *Plan view and bed profile of the Cavaillon River (origin of x at Dory weir).*

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be used to evaluate the discharge entering the study reach. This specific stage-discharge relationship was measured in situ for some discharges, unfortunately only for rather limited discharges [Carlier d'Odeigne and Soares-Frazao, 2016]. In order to extend the relationship to larger discharges, the weir was numerically modelled [Roelandt and Verschoore, 2016] using free software OpenFoam for computing a series of 2D slices, each slice with its own measured profile. In the classical relation for the discharge Q as a function of the water head H over the weir crest of width L:

$$Q = \mu L\sqrt{2g}H^{3/2}, \tag{1}$$

an average discharge coefficient m = 0.45 could be estimated from this numerical approach, which corresponds to a decrease of about 10 % of its conveyance compared to standard weirs.

The Dory weir was seriously damaged by the flood of October 2016 induced by Hurricane Matthew. The right abutment of the weir was circumvented by the flow with two consequences: a serious problem for the irrigation network that was supplied by the water rise controlled by the weir, and the loss of measurement capability of the weir. The closing of the bypass is planned but it is clear that a new survey of the weir will be required for accounting for the new damages on the weir itself.

The downstream boundary condition of the model is located at Grand Place, about 4 km upstream from the mouth of the river. At this location, the water level is recorded using an OTT PLS device and the discharge is measured by an OTT SLD water velocimeter. However, in low-flow conditions, this latter device is no more submerged and no discharge measurements can be obtained.

Because of the proximity of this downstream boundary condition to the mouth of the river, the influence of the tidal sea level variations on the water level at this station was investigated. A 24-hour measurement campaign was carried out to record the water level at Grand Place and at three other stations located further downstream. The results are illustrated in Fig. 7. While the influence of the tide is clearly visible close to the mouth of the river, its influence at Grand-Place appears to be negligible.

III.3. Calibration of the river roughness

Evaluation of the river roughness was carried out using various methods. First, the roughness was evaluated from

Fig. 6 : *Damaged Dory weir.*

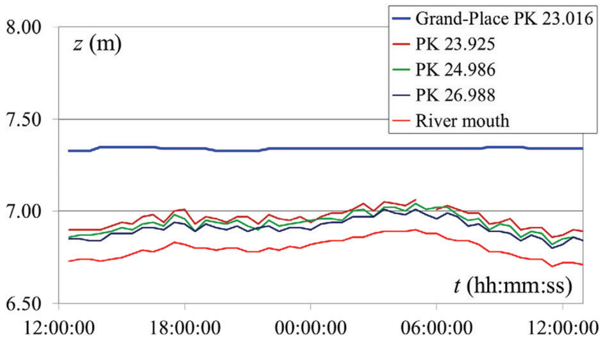


Fig. 7 : *Water-level evolution during a tidal cycle at Grand-Place.*

the sediment grain-size distribution, this latter obtained by the classical Pebble Count Method [Wolman, 1954] for each of the surveyed cross-sections. Then the water profile computed with this approximate value was compared to some measured water levels and the roughness was adjusted to better fit the observations. Unfortunately, this fitting was only possible before Hurricane Matthew, for limited discharges and water depths. New evaluations have to be carried out for instance from flood marks of the hurricane.

IV. FLOOD SCENARIOS AND FLOODING MAPPING

The Cavaillon River is located in a region where hydrological extremes are frequent. So, determining flood and inundation risk is one of the main goals of the present study. To this end, possible inflow hydrographs need to be constructed and then routed throughout the river to identify the extent of the consequently flooded area.

IV.1. Input hydrograph

Statistical analysis of maximum and minimum daily discharges at the Cavaillon station during the periods 1925-1941 and 1976-1980 allowed estimating the flood flows corresponding to return periods of 10, 20, 50 and 100 years. The comparison of these flow values with the flow rates estimated from empirical formulas and during Hurricane Matthew shows their likelihood. Peak flows at tributary outlets are estimated from the direct transposition method of a neighbouring station, with an adjustment corresponding to the ratio of the respective watershed area. The Galton type synthetic hydrograph method [Boutoutaou and Zeggane, 2014], expression (2), was used for the construction of probable flood hydrographs at the Dory spillway and at confluences of the tributaries with the main river:

$$Q(t) = Q_p\left(\frac{t}{t_{p.}}\right)^{-0.1}\exp\left(-\frac{1}{2}\left(\frac{\ln\left(t/t_p\right)}{k}\right)^2\right), \tag{2}$$

Such a synthetic hydrograph for the Cavaillon River is represented in Fig. 8 for an assumed peak discharge Q_p of 550 m³/s at time t_p = 15 h. For Hurricane Matthew, the peak discharge is not known, and could not be measured because severe erosion occurred at the location of the Dory weir that was circumvented by the flow (Fig. 6). However, from the

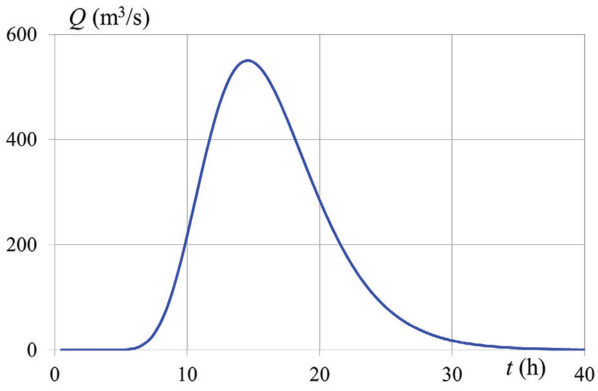


Fig. 8 : *Example of synthetic hydrograph for a peak discharge of 550 m*^{3}*/s.*

scarce information currently available, the peak discharge during this event was estimated to 1140 m^3/s. So, using this value and equation (2), an inflow hydrograph for this situation could be constructed.

IV.2. Mapping of potentially flooded areas

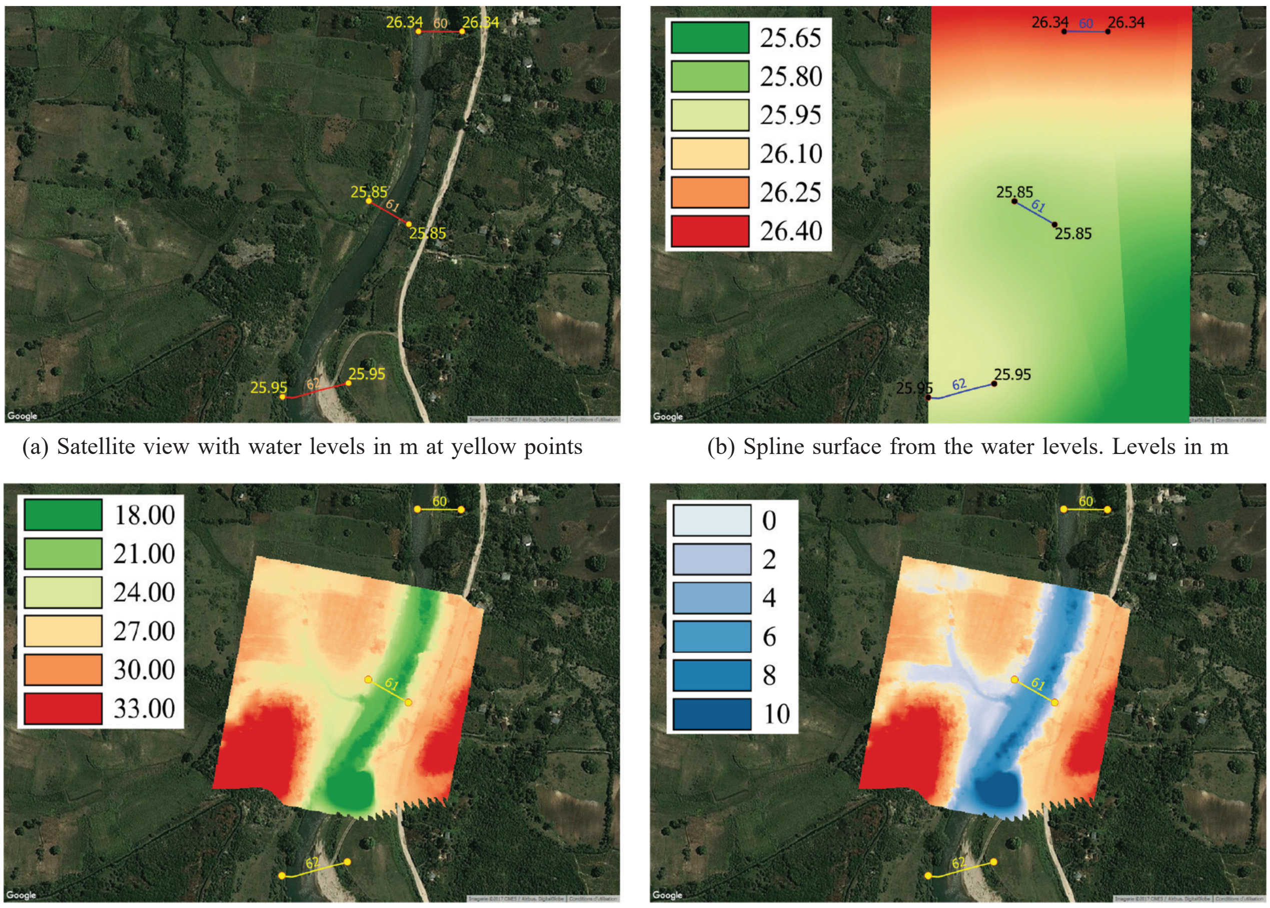
The following classical steps for evaluating the inundation extent along the Cavaillon River were applied. Firstly, the water profile is computed assuming either a 1D steady-flow or a 1D transient flow, depending on the transient character of the flood. The computed water levels are then imposed at the left and right ends of the measured cross-sections, the distance between the cross-sections being approximately 200 m. An example is given in Fig. 9 for an assumed constant discharge of 1140 m^3/s, close to the assumed peak during Hurricane Matthew. The computed water levels are imposed at the yellow points of Fig. 9(a). For example the water level at section 61 is 25.85 m.

These points form a shapefile that can be used in GIS software (in the present study the free software Q-GIS was used) as support of a spline interpolated raster surface (Fig. 9(b)) that could represent approximately the flood water table, even in river bends.

The spline interpolated raster surface may be created with any density but, as the result has to be compared to the Digital Terrain Model raster, the same density (meshes of 0.10 m) has been adopted for the spline surface as for the DTM, this latter being represented in Fig. 9(c). The spline surface of Fig. 9(b) is then compared to the DTM of Fig. 9(c). In case of positive difference between spline surface water table and DTM terrain levels, a new raster (in blue in Fig. 9(d)) is generated, representing the water depth at the different raster cells, and consequently representing the extension of the potential inundation.

V. IDENTIFICATION OF ISSUES AND ANALYSIS OF VULNERABILITY

Haiti is characterized by an extreme poorness and a lack of public resources. That means that any public effort in



(a) Satellite view with water levels in m at yellow points

(b) Spline surface from the water levels. Levels in m

(c) DTM (ground levels in m)

(d) Flooding map (in blue) and water depth

Fig. 9 : *Mapping of inundated areas around cross-section 61 (background from Google Earth).*

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order to improve the protection of the population against natural hazards has to be closely optimised.

Regarding the optimal management of risk mitigation measures, a popular and powerful approach is the Analytic Hierarchy Process (APH), which is a multi-criteria hierarchical technique, used to analyse the vulnerability of the various zones of a territory, so supplying a decision tool for the works to be carried out in priority. AHP relies on a technique for defining criteria to decide between various issues [Saaty, 1980].

The first stage consists in defining the zones potentially affected by the natural hazard. The goal is precisely to hierarchize these zones in term of vulnerability and need for protection.

In order to generate this hierarchy a series of criteria of vulnerability are selected. Generally these criteria include issues that can be clearly quantified and others that are trade-off, difficult to quantify objectively. To circumvent this difficulty, the classical way is to first listen to the local actors directly involved in the work of reducing vulnerabilities and therefore capable of perfectly knowing the reality on the field. Actors are invited to give their own perception of the risk, their definition of the vulnerabilities, the weight that they attribute to them and their hierarchy. Paired comparisons between issues progressively lead to a kind of consensus about the weight of each of them in the decision-making. The result is a weighting factor for each of the criteria.

Finally, a GPS survey of all the zones potentially affected is realised and crossed with such weighted criteria in order to characterise the vulnerability of each zone.

V.1. Criteria for vulnerability analysis

The vulnerability of a zone to flooding is essentially governed by its land use: it is clear that a dense urbanized zone is more vulnerable than a rural territory. Fig. 10 presents a list of possible criteria related to land-use.

Besides criteria related to environment and material goods, a major criterion is based on human issues. A simplified view could be to consider that this latter criterion is just a number: number of inhabitants, number of schools, number of firms, etc. But the reality is more complex. For example, adult inhabitants are able to face a moderate inundation without personal damage, while young children and old people are unable to react without help. It is also delicate to distinguish between different types of damages: a person may be injured by the flood, but even without being injured, this person can lose a part his house or of his belongings that can finally affect his well-being and his health. Also environmental issues may interfere with human issues: if a water source is polluted by the flood, damages for the health of a whole community may be disastrous. This means that the task to attribute a weight to all these criteria and issues is not easy.

V.2. Criteria weighting

The weighting process is intrinsically subjective and what is proposed by AHP is to use this subjectivity as a tool for converging to a consensus.

The assessment of the vulnerability criteria depends on the judgment made on the basis of the knowledge gained on the field by the local actors audited on the degree of

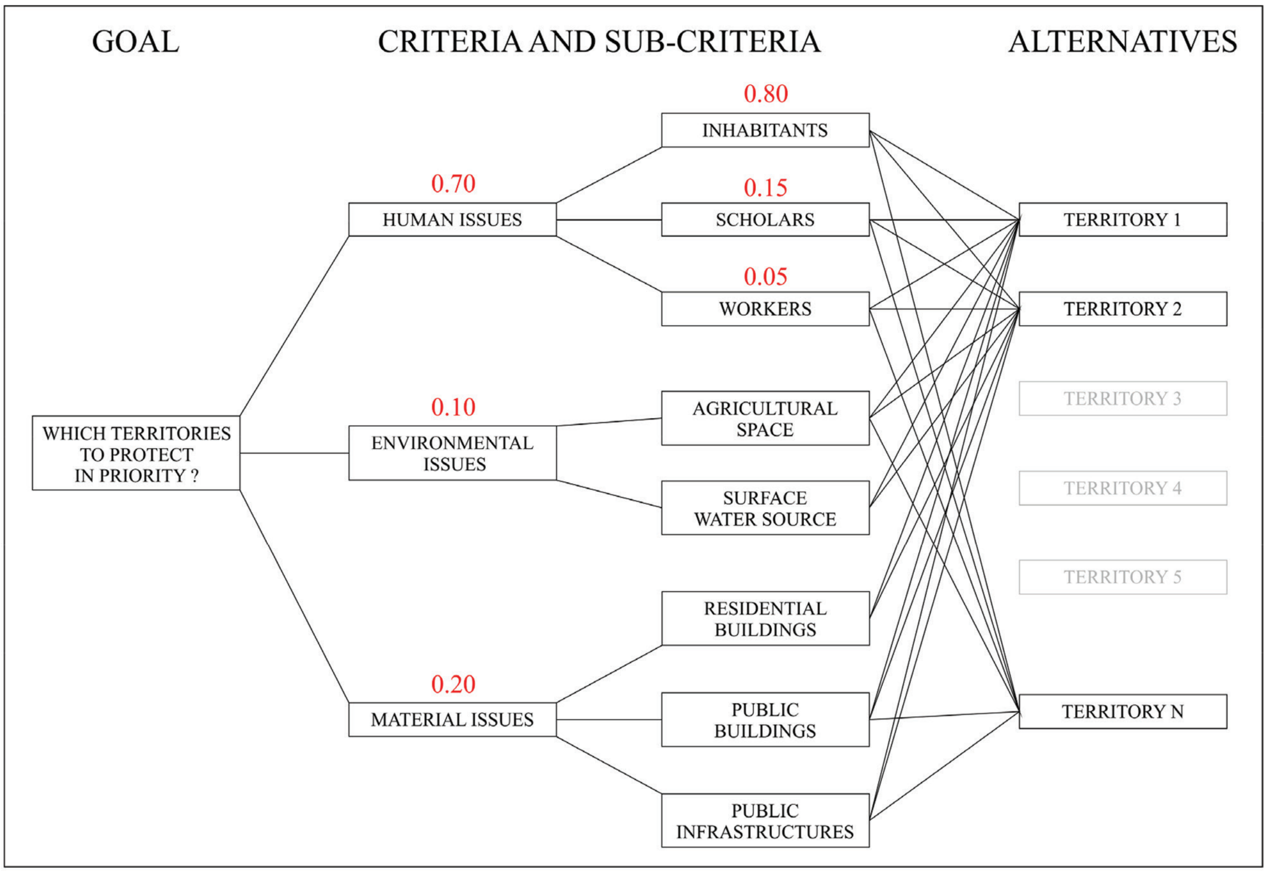


Fig. 10 : *Analytic Hierarchy Process scheme.*

vulnerability of the zones to the submersion by the water. The stakes are compared two by two and quantification is made according for instance to a specific scale based on the Saaty criteria given in Table 1.

That means that, for example, such panels of local decision makers have considered, after discussions and averaging of the various opinions, that human issues are very important compared to environmental ones. So if we give a weight 1 to this latter criterion, the human criterion presents a weight 7. If material issues are judged as between equal and moderately more important than environmental one, a number 2 is assigned. This yields to the weighting coefficients indicated in red in Fig. 10.

The game continues at the level of sub-criteria. In Fig. 10, only the human issues weighting is indicated as the process is still running and those weighting were issued from a small community of decision-makers playing as testers of the method.

It is interesting to notice that some weighting coefficients may appear as controversial. For example, considering such a distance between inhabitants and scholars criteria could appear as shocking for external observers: how is it possible to consider that scholars are less worth to be saved than general population? But local people will consider that they will not send their children to school in case of hurricane alert, while they do not always have the choice to leave their housing in that case.

V.3. Vulnerability mapping for the Cavaillon City

The city of Cavaillon was chosen to apply the vulnerability mapping methodology as this city comprises numerous infrastructures of different types. However, due to the unexpected extent of the flooded area, the major part of the zone was not flown by the UAV. As a consequence, no good-quality topographical data exist for the city, and mapping the inundated area as done in Fig. 9, following the simulation of a synthetic hydrograph corresponding to the probable Hurricane Matthew flood, revealed impossible in the area occupied by the city.

As the city of Cavaillon was seriously impacted by the flood consecutive to Hurricane Matthew in October 2016, it was decided to apply the vulnerability methodology using the field measured extent of the inundated area. Indeed, a preliminary survey of the inundated zone was carried out in the weeks after the event, so delimiting the inundated area. This area was then subdivided in zones of homogeneous land-use, for instance blocks of buildings, or agricultural fields (Fig. 11(a)). The river itself determines a natural limit, as well as roads and paths.

Applying the AHP process to the vulnerability of each zone allows defining the vulnerability map. Fig. 11(b) gives such an example applied only to the criterion of human issues, i.e. mainly the criterion of the inhabitants.

It can be seen that the most vulnerable areas are located in the centre of the town of Cavaillon and along the access roads to the city where concentrations of populations and infrastructures are high. In these areas, the human stake is more decisive. This logic is similar for most municipalities in Haiti faced with floods, as people tend to regroup in the city centre and near roads.

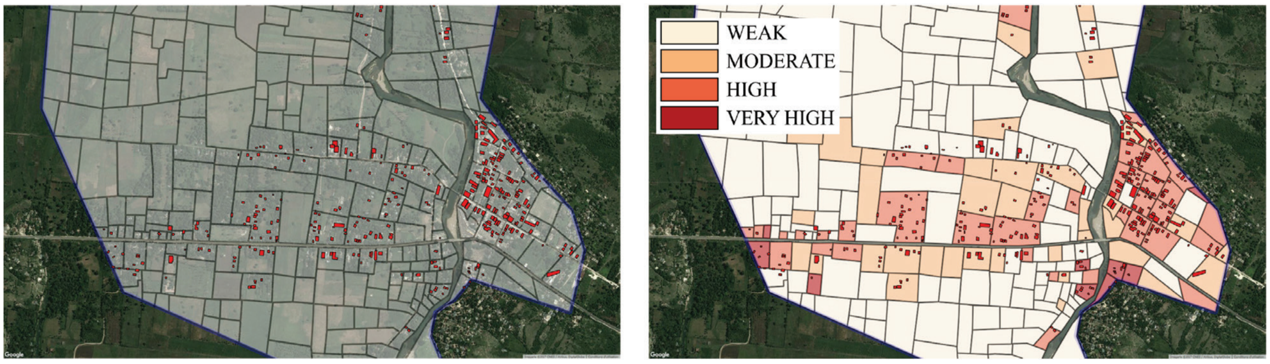
Table 1 : Binary comparison scale used to assess vulnerability criteria [Saaty, 1980].

Expression of one criterion relative to another	Intensity of importance
Same importance	1
Moderately more important	3
Much more important	5
Very important	7
Extremely more important	9

VI. CONCLUSIONS AND PERSPECTIVES

This paper presents the first steps achieved in the direction of establishing a methodology for flood risk mapping around Haitian rivers. The methodology comprises (1) the acquisition of field data regarding topography, bathymetry, roughness and boundary conditions; (2) the construction and calibration of a hydraulic model for the river; (3) the definition of flood scenarios and mapping of the corresponding inundated area; (4) the evaluation of the vulnerability of the areas around the river; (5) the definition of the risk posed by the different flood scenarios according to their probability of occurrence and to the estimated vulnerability of the concerned areas.

This paper illustrates the difficulty to apply such a methodology on the field in a context like the one prevailing in Haiti. As no accurate field data exist, step (1) was achieved by a combination of direct field survey and UAV-based



(a) Inundated area in October 2016: subdivision in zones of homogeneous land-use(main buildings in red)

(b) Inundated area in October 2016: degree of vulnerability of each zone (main buildings in red)

Fig. 11 : *Vulnerability mapping.*

photogrammetry, providing accurate data but only over limited areas, sometimes too limited to cover the hazardous zone. Step (2) should still be improved, as the calibration of the hydraulic model could only be achieved with very scarce discharge and water level data. As regards step (3), further analysis of the available hydrologic data and especially of the recent Hurricane Matthew should allow the definition of inflow hydrographs corresponding to better-defined return periods. Regarding step (4), at the moment, only few representatives of the local population contributed to the definition of the vulnerability weighting of the different areas in the city. A dedicated field research is foreseen to obtain more information about the actual preoccupation of the inhabitants. All these improvements will then allow reaching step (5), i.e. crossing the vulnerability map to a hazard map to get a distribution of risks in the city that will hopefully help the local authorities to better select the appropriate actions for a sustainable reduction of this risk.

VII. ACKNOWLEGMENTS

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